DC Fault Analysis in Bipolar HVDC Grids

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***Abstract*—Bipolar High Voltage Direct Current (HVDC) is expected to form the backbone of future HVDC grids because it offers advantages in terms of redundancy and added flexibility in developing and operating the system. This comes at the cost of introducing unbalances in the system. However, most DC fault studies until now have assumed a monopolar configuration or a balanced operation of a bipole, and thereby not addressing the challenges that comes with the operation of bipolar systems, such as the influence of unbalanced conditions and grounding relocation on the fault behavior and DC protection systems. This paper deals with DC fault analysis in bipolar HVDC grids, particularly taking those unbalances and grounding relocation into consideration. DC fault behavior under unbalanced conditions and different grounding locations is investigated via simulation studies using PSCAD/EMTDC. The influence of unbalances and groundings on the development of protection systems is evaluated.**

***Index Terms*—Bipolar configuration, HVDC grid, DC fault, Unbalances, Grounding.**

I. INTRODUCTION

Meshed HVDC Grids are seen as a viable option for the future transmission system in order to allow massive integration of often remotely-located renewable energy sources and to provide increased reliability and flexibility at a lower cost. Although multi-terminal HVDC systems in operation today are based on LCC (Line Commutated Converter) technology, it is considered that VSC (Voltage Source Converter) technology is more suitable to build meshed DC grids [1]. VSC technology provides better capabilities such as increased controllability, power reversal by changing the current direction and common voltage enabling straightforward shunt connection. Moreover recent development of the VSC technology has lead to converter losses which are comparable to those of the LCC technology. VSC-based HVDC systems are considered as a key technology for the European Supergrid, which will connect the AC grids and offshore wind farms through a HVDC grid [2]. In China, two pilot multi-terminal VSC HVDC projects have already been commissioned and are in operation [3], [4].

Existing VSC HVDC links are mainly used with symmetrical monopolar configurations. However, future HVDC grids are expected to develop into systems with a bipolar configuration. The bipolar configuration offers increased flexibility, e.g. for post-fault operation and higher extensibility in developing HVDC grids. Through unbalanced operation, a bipolar link still has half of the capacity in case of an outage of one pole. In addition, a bipolar grid can be extended with bipoles or with monopolar tappings [5], [6]. The importance of system configuration and grounding has been acknowledged, especially in the area of system protection, since the fault currents largely depend on the grounding [1], [5] and [6]. In recent years, more and more attention has been paid to the bipolar configuration. Nevertheless, most fault detection and protection studies have either implicitly assumed or explicitly limited to a symmetrical monopolar configuration or a balanced operation of a bipolar configuration, thereby disregarding the effect of the unbalances in bipolar grids. Up to now, the influence of the location of the grounding points on the fault behavior in bipolar systems has never been addressed. In [7] and [8], a solidly grounded bipolar configuration with sea return under balanced operation is used to analyze the fault currents, and possible fault clearing options. In [9], the specific case of a bipolar scheme with a metallic return was considered to calculate fault currents in a MTDC system for different grounding options. The impact of the HVDC topology on network faults is investigated in [10], but only balanced bipolar operation is considered. The situation is very similar in the area of HVDC grid protection studies. For example, the authors proposed a traveling-wave based protection algorithm considering a symmetrical monopolar configuration in [11]. A wavelet energy based differential protection is proposed in [12] for a bipolar system; however, the paper did not consider unbalanced operation.

At this stage, the influence of the unbalances and the grounding location in bipolar HVDC grids on fault behavior and protection systems are not fully understood. This paper especially focuses on selective primary protection algorithms such as [11], which normally use voltages and currents of the first few milliseconds to detect and identify the fault. It is essential to evaluate whether these signals are affected by the unbalances and grounding configuration or not. This paper aims at providing a first indication of the potential influence by analyzing DC fault behavior under unbalanced conditions and different grounding locations in bipolar HVDC grids. The paper is organized as follows. Section II gives brief introduction on system configurations and grounding options. In section III, the test system and case studies are presented, and in section IV the fault behaviors under different conditions are explained using travel wave theory. Section V analyzes the influence of the unbalances and groundings on the protection system. The conclusions are given in section VI.

II. CONFIGURATION AND GROUNDING OF BIPOLAR HVDC GRIDS

Future bipolar DC grids are expected to have intrinsic unbalances, which could be unbalanced power flow or unbalanced configuration due to an outage of a converter, a line or through monopolar tappings. The influence of such unbalances on the fault behavior has to be properly studied in order to develop robust protection systems. In addition, the grounding points in a meshed DC grid might change due to system reconfiguration and the protection system needs to be able to detect any type of fault regardless of the fault location and the distance to the grounding point. With a bipolar backbone, the DC grid can have various possible configurations [6]:

a) bipolar grid with metallic return
b) bipolar grid with metallic return and asymmetric monopolar tapping
c) bipolar grid with metallic return and symmetric monopolar tapping
d) bipolar grid with metallic return and bipolar tapping with earth return

Configuration b), in particular, is intrinsically unbalanced even during normal operation.

During normal operation, a bipolar system operates the two poles with practically the same DC voltage and current so that the neutral current remains near zero. In a point-to-point bipolar HVDC link, the healthy pole conductor can be used as the return path in case of a single pole outage. However, a low voltage dedicated conductor (metallic return) is required to operate as the return path in meshed HVDC grids. A bipolar grid can be high-impedance or low-impedance grounded. In case of high-impedance grounding, the fault currents are effectively limited at the cost of higher insulation requirements. In low-impedance grounded systems the overvoltages are limited, but the fault currents may reach very large values, which results in more stringent time constraints of the protection system. Due to the limitation of insulation materials and their costs, especially for cable systems, low-impedance or solidly grounded HVDC grid alternatives are seen as more advantageous options in the long run [1]. For the reasons described above, we focus on a solidly grounded bipolar grid with metallic return under three scenarios: balanced operation, unbalanced conditions and different grounding locations.

III. Test System and Considered Case Studies

A. Bipolar Test System

A three-terminal bipolar test system was built based on the HVDC grid test system provided in [13], implemented in PSCAD/EMTDC. The three-terminal bipolar test system, shown in Fig. 1, is a bipolar cable-based configuration with metallic return, with a dc voltage of ±320 KV. For the sake of simplicity, the metallic return is dimensioned the same as the main cables. The bipolar test system is solidly grounded at converter station 3.

The capacity of the converters are reduced to 500 MVA, and the parameters of the converters are scaled accordingly. Main parameters of the DC grid and converters are shown in Table I. The bus filter reactor of 10 mH is removed to fully incorporate the dynamics of the converters, while the series inductor of 100 mH associated with the DC breakers is included in the bipolar test system since it plays an important role in selective protection [11]. The controllers of converter 1 and 2 are set to control the DC voltage with the same power-voltage droop ratio, while converter 3 controls the active power. The only protection implemented is overcurrent protection of the converter, which will block the converters once the current exceeds the pre-defined thresholds. The aim is thus to have a first indication of the differences in fault currents when no line protection is applied.

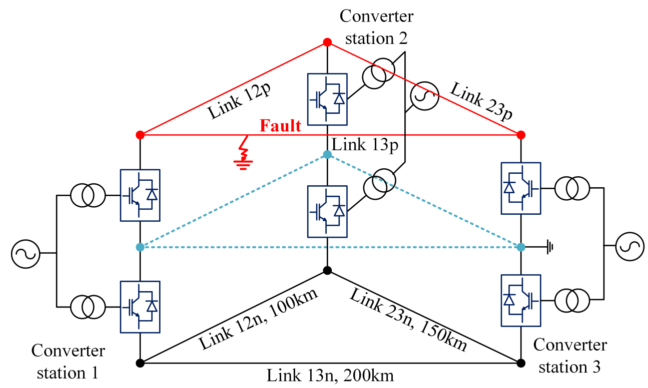

Fig. 1. Three-terminal meshed bipolar HVDC grid test system

TABLE I
CONVERTER AND GRID PARAMETERS

Converters		
Rated Power	500	[MVA]
DC Voltage	320	[kV]
AC grid voltage	400	[kV]
AC converter voltage	185	[kV]
Arm capacitance C_{arm}	65.1	[μF]
Arm inductance L_{arm}	38.2	[mH]
Arm resistance R_{arm}	0.4	[Ohm]

TABLE II
SIMULATION CASES AND CONDITIONS

Case Study		**Conditions**	
No.	Suffix used in figures	Power Flow (+/-:inverter/rectifier)	Grounding Location
1	B (g3)	Balanced, P_{1p}=P_{1n}= -200MW, P_{2p}=P_{2n}= -300MW, P_{3p}=P_{3n}= 500MW	station 3
2	U	Unbalanced, P_{1p}= -500MW, P_{2p}= 0MW, P_{3p}= 500MW	station 3
	LO	Balanced (same as Case 1) with Link 12p open	station 3
3	g2	Balanced (same as Case 1)	station 2

B. Case Study

The DC fault studied in this paper is a pole-to-ground fault, considering that it is the most probable fault in a cable-based system. A solid pole-to-ground fault in the middle of the cable connecting to converter 1 and converter 3 of the positive pole (Link 13p), is incepted at time 0 s in the simulation to investigate the natural fault response. Measurements are taken at both ends of the cables, where the protective relays are expected to be located. Three case studies are considered in this paper. Simulation cases and conditions are summarized in Table II. Case 1 is a reference case, where the pre-fault condition is under balanced operation. Case 2 investigates two unbalanced conditions, unbalanced power flow and unbalanced configuration. Case 3 investigates the influence of different grounding locations.

1) Case 1: Balanced operation: As a reference case, the DC fault behavior under balanced operation is studied. In the pre-fault steady-state, converter station 1 and 2 export 400 MW and 600 MW respectively to converter station 3, with power evenly shared between the positive and negative poles.

Fig. 2 shows the currents and voltages at both ends of Link 13p where the pole-to-ground fault is applied and one end of the healthy cables, Link 12p and Link 23p. Currents and voltages of the negative pole and the metallic return are shown in Fig. 3. From the simulation results, the characteristics of a pole-to-ground fault in a bipolar system can be summarized as follows:

- As shown in Fig. 2 (a) and (c), currents in the faulted cable increase very fast, with a maximum derivative of 2 kA/ms. On the contrary, currents in the healthy cables of the same pole increases much slower, with maximum derivative of 1 kA/ms. The voltages of the faulted cable drop to negative values within 1 ms after fault inception as illustrated in Fig. 2 (b). The voltages change much slower in the healthy links of the same pole due to the smoothing effect of the series inductors. The differences of these currents and voltages are normally used to identify the faulted link.
- During the transient, the currents of the negative pole increased. However, they did not exceed the thresholds of the overcurrent protection of the converters. Overvoltages occurred on the negative pole, with a maximum magnitude of 1.22 pu measured at Link 12n near the terminal of converter 1, which need to be properly handled in real operation.
- Fig. 3 (b) shows that the steady-state fault current at the fault location is about -20 kA, which is contributed almost equally from both directions of Link 13p as indicated by I13p and I31p in Fig. 2 (a). Large steady-state currents also flow in the metallic returns. The negative voltages at the ungrounded sides of the metallic return reach very high values, with a maximum overvoltage of -85 kV at converter station 1.

2) Case 2: Unbalanced conditions: Two unbalanced conditions, unbalanced power flow and unbalanced configuration, are considered in the second case study. In the unbalanced power flow case, U (see Table II for details), the power set points of the positive converters are changed, while negative converters remain the same as in the reference balanced power flow case. In the unbalanced configuration case, LO, the cable connecting converter 1 and converter 2 of the positive pole, Link 12p is opened while keeping the power set points of all the converters the same as in the reference balanced power flow case.

Simulation results are shown in Fig. 4 and Fig. 5. The suffixes of the signals are in correspondence with the names of the simulation cases listed in Table II. Fig. 4 compares voltages and currents of the faulted pole under the three conditions in order to investigate the influence of the unbalances on selective primary protection algorithms. Since only the fault behavior in the first milliseconds is of interest for selective primary protection algorithms, the voltages and currents of the faulted pole are plotted up to 15 ms in Fig. 4. Fault currents at the fault location, currents and voltages of Link 13n of the healthy pole and the metallic return are shown in Fig. 5 in order to investigate the influence both on the transients and the steady-states. From the simulation results we can reach the following conclusions:

- As shown in Fig. 4 (a), in the first 2 milliseconds, the unbalanced conditions have insignificant impact on the voltages of the positive (faulted) pole. The currents of the faulted cable increase at similar rate, with more differences after 2 ms. As long as fast selective primary protection is concerned, unbalanced conditions will not

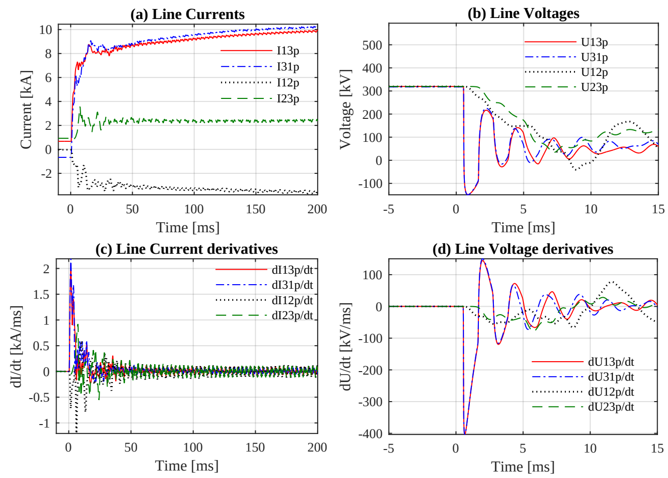

Fig. 2. Currents and voltages of the faulted pole, Case 1 Balanced operation (voltages and their derivatives are only shown up to 15 ms)

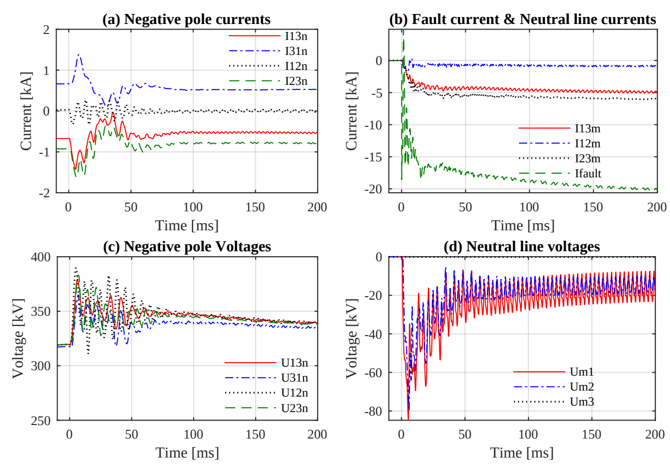

Fig. 3. Currents and voltages of the healthy pole and the metallic return, Case 1 Balanced operation

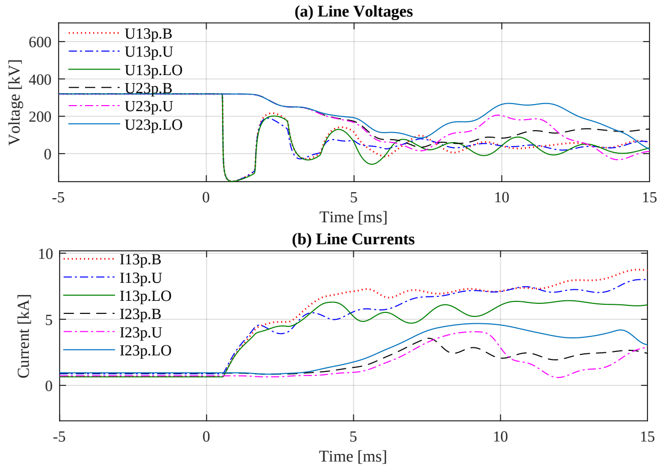

Fig. 4. Currents and voltages of the faulted pole, Case 2 Unbalanced condition (B: Balanced operation, U: Unbalanced power flow, LO: Unbalanced configuration, Link 12p open)

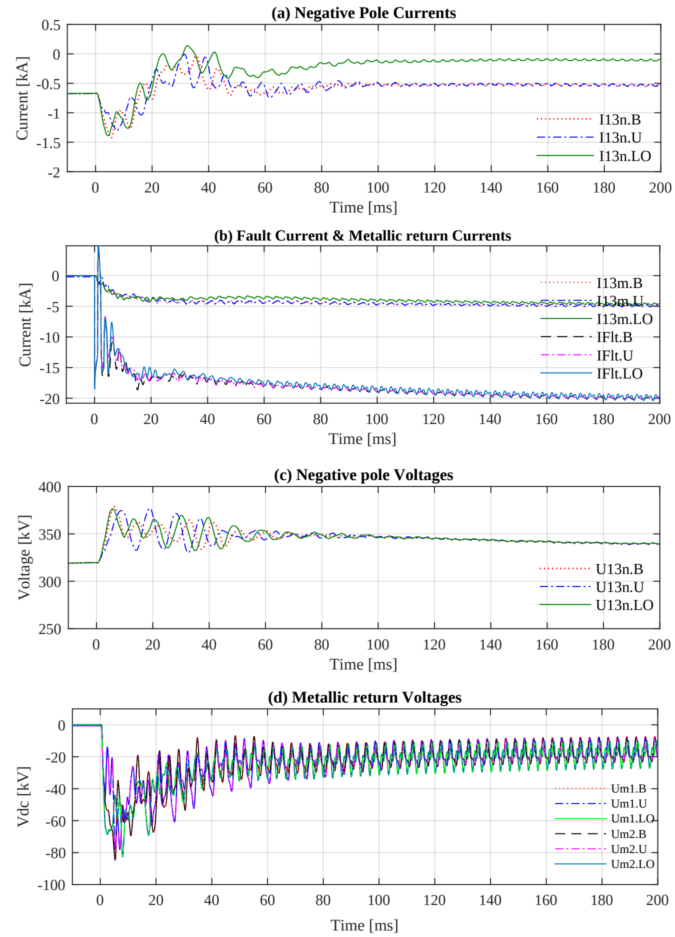

Fig. 5. Currents and voltages of the healthy pole and the metallic return, Case 2 Unbalanced condition (B: Balanced operation, U: Unbalanced power flow, LO: Unbalanced configuration, Link 12p open)

significantly affect the detection algorithms in systems with large series inductors. However, currents and voltages diverge as the fault develops in the grid, which imply influences on backup protection.

- As shown in Fig. 5, current variations and overvoltage levels of the negative (healthy) pole also have similar levels despite the unbalances. In addition, Fig. 5 (d) shows that the negative voltages at the ungrounded sides of the metallic return reach similar values as well.
- Balanced and unbalanced power flow (cases B and U) show same steady-state fault currents because the steady-state fault currents are determined by the grounding location and fault location. In the case with positive Link 12p open (case LO), the steady-state currents are different since routes to the grounding location differ. However, in selective primary protection systems, these steady-state differences are of little importance since it falls out of the time range of the protection system.

3) Case 3: Different grounding locations: In a bipolar DC grid with metallic return, the system is normally low-impedance grounded with one or multiple grounding locations. In the course of operation, the groundings of the bipolar grid might change due to possible contingencies or operational requirements. A robust protection system has to be able to detect any faults irrespective of the fault location and the distance to the grounding point. In this study, pole-to-ground faults with different grounding locations are simulated. In the case g2, the system is grounded at converter station 2 instead of converter station 3 (case g3). The fault currents and voltages are compared in Fig. 6 and Fig. 7. The following conclusions can be drawn:

- Fig. 6 shows that in the first few milliseconds after fault inception, voltages and currents of the faulted cable are almost overlapping each other regardless of the grounding locations. Similar to the unbalanced conditions study, fast selective primary protection algorithms are thus not expected to be significantly influenced by different grounding locations.
- Influences on backup protection are implied since currents and voltages diverge as the fault develops in the grid.
- Current variations and overvoltages of the negative pole and the metallic return are of similar level as shown in Fig. 7. Fig. 7 (d) shows that the maximum overvoltage of the metallic return appeared at station 1 when converter station 3 (case g3) is grounded, while the maximum overvoltage appeared at station 3 when station 2 (case g2) is grounded. The steady-state currents differ as a result of the different grounding locations and the consequently different resistances of the fault paths.

IV. Fault Behavior in Bipolar Systems with Large Series Inductors

According to the simulation studies, in the first few milliseconds after fault inception, the fault behavior in terms of voltages and currents of the faulted pole in cable-based

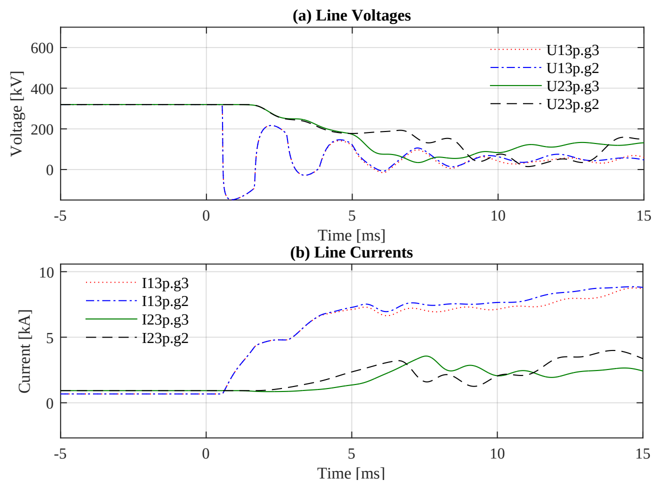

Fig. 6. Currents and voltages of the faulted pole, Case 3 Different grounding location (g3: grounded at station 3, g2: grounded at station 2)

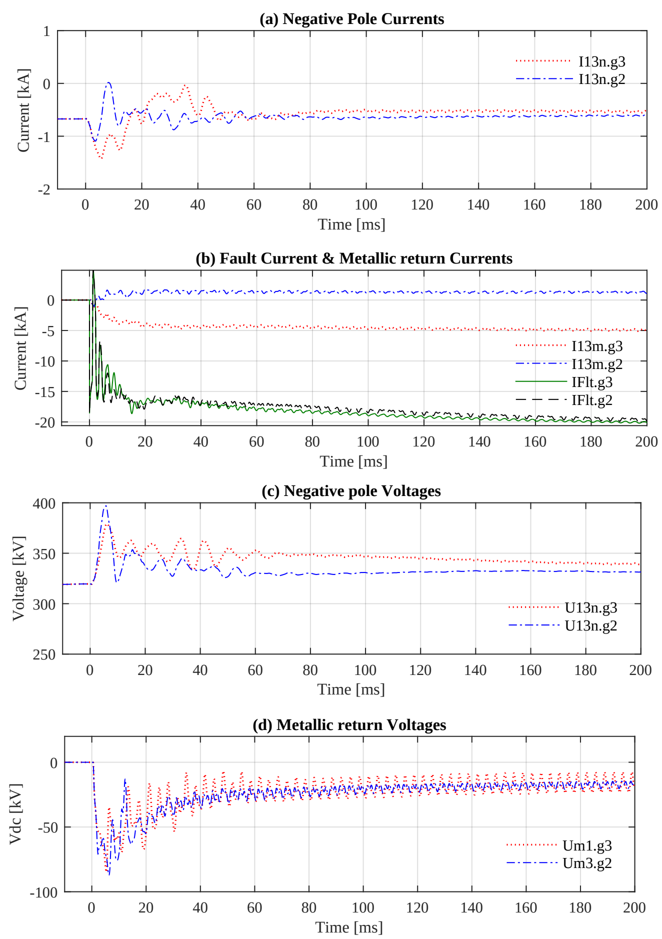

Fig. 7. Currents and voltages of the healthy pole and the metallic return, Case 3 Different grounding location (g3: grounded at station 3, g2: grounded at converter 2)

systems, is not significantly affected by unbalanced conditions and grounding locations. This behavior can be explained by the traveling wave theory. Fig. 8 illustrates a simplified path of a traveling wave on a faulted cable terminated with series inductor where solid pole-to-ground fault can be considered as switching in a voltage source with negative polarity at the instant of fault inception. The wave created at the fault location travels to the cable termination, where it is partly reflected back and partly transmitted to the rest of the grid. Until then, the fault waves are identical regardless of unbalances and grounding locations. In the case studies, it takes about 0.55 ms for the fault wave to reach the cable termination which is 100 km from the fault location. Most importantly, the considerably large series inductors at both terminals of the cable reflect most of the first incident wave back, hence the fault wave is largely confined within the faulted cable. As more reflections and refractions happen as the fault develops, fault waves diverge more because the fault paths are different in balanced and unbalanced conditions.

As a comparison, Fig. 9 presents simulations with series inductors of only 1 mH under unbalanced configurations. As shown in Fig. 9, significant differences in voltages and currents can be observed even in the first milliseconds.

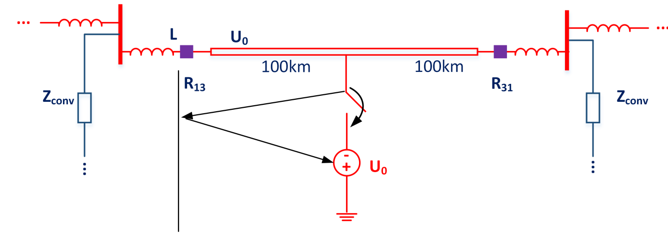

Fig. 8. Traveling wave on a faulted cable terminated with inductor

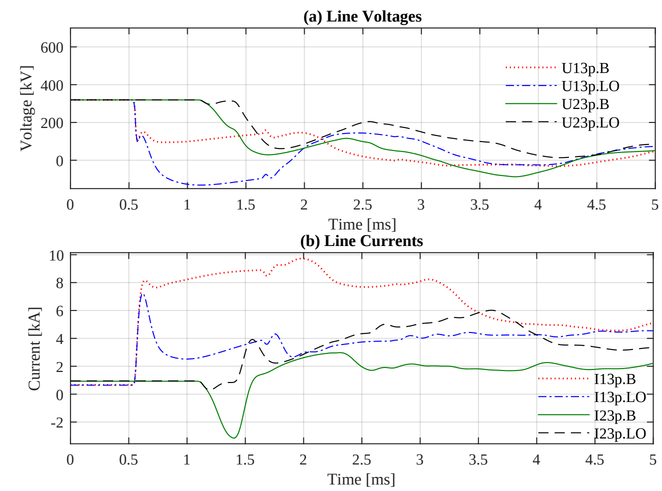

Fig. 9. Fault currents and voltages of the faulted pole, series inductor = 1 mH (B: Balanced operation, LO: Unbalanced configuration, Link 12p open)

V. Influence on Protection

If only the first voltage or/and current wave is used to detect and identify the fault in a cable-based system, which is commonly proposed in primary protection [11], [14], [15], then the sensitivity of the protection algorithms to unbalances or grounding relocation in a bipolar DC grid is mainly determined by the series inductor. If series inductors are installed at the ends of the DC cable, it can be expected that the impact of the unbalances and grounding relocation on the protection algorithms will not be significant. This is especially true in non-unit protection methods [11], which normally involve using fast DC circuit breaker to interrupt the fault current, and the proposed DC circuit breaker are equipped with series inductors to limit the rise rate of the fault current [16], [17]. Therefore, protection concepts which adopt non-unit protection methods can be expected to be relatively insensitive against unbalances and grounding relocation. On the contrary, protection concepts which do not include series inductors or use fault voltage and/or current waves in longer time range will be affected by the unbalances and grounding relocation to a certain extent. In these cases, more detailed simulation studies are required in order to establish robust and selective relay settings.

Since the operation time range of backup protection falls into the region where faults behave differently under unbalanced conditions or grounding relocation [15], [18], detailed parametric studies are needed when developing backup protections for bipolar grids. In addition, failure mode of protection equipment might also change the fault behavior and play an important role in backup protection.

VI. Conclusion

This paper analyzed DC fault behavior under unbalanced conditions and different grounding locations in a three-terminal bipolar test system. If series inductors are placed at both ends of the cables, fault behavior in the first milliseconds is not significantly influenced by unbalanced conditions or grounding relocation since the inductors reflect most of the fault waves. The voltages and currents diverge more as fault develops in the grid regardless of the presence of series inductors.

As for the impact on the protection system, as far as the selective primary protection is concerned, the presence of series inductors and time range of signals used for identification are the most determining factors. If large series inductors are placed at the ends of the DC cable, the selective primary protection algorithms are not likely to be affected by the unbalances and grounding relocation. However, the influence on the backup protection systems is implied since the operation time range of the backup protection falls into the region where faults behavior differently under unbalanced conditions or different grounding locations.

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